# MEaSUREs Greenland Quarterly Ice Sheet Velocity Mosaics from SAR and Landsat, Version 5

# USER GUIDE

### How to Cite These Data

As a condition of using these data, you must include a citation:

Joughin, I. 2023. *MEaSUREs Greenland Quarterly Ice Sheet Velocity Mosaics from SAR and Landsat, Version 5*. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.5067/V5KW64S63OSN. [Date Accessed].

### Literature Citation

As a condition of using these data, we request that you acknowledge the author(s) of this data set by referencing the following peer-reviewed publications.

Joughin, I., B. Smith, I. Howat, T. Scambos, and T. Moon. 2010. Greenland flow variability from ice-sheet-wide velocity mapping, Journal of Glaciology. 56. 415-430. https://doi.org/10.3189/002214310792447734

Joughin, I., B. Smith, and I. Howat. 2018. Greenland Ice Mapping Project: ice flow velocity variation at sub-monthly to decadal timescales, The Cryosphere. 12. 2211-2227. https://doi.org/10.5194/tc-12-2211-2018

FOR QUESTIONS ABOUT THESE DATA, CONTACT NSIDC@NSIDC.ORG

FOR CURRENT INFORMATION, VISIT https://nsidc.org/data/NSIDC-0727

National Snow and Ice Data Center

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# 1 DATA DESCRIPTION

This data set, part of the NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) program, contains quarterly ice velocity mosaics for the Greenland Ice Sheet posted at 200 m. Velocities are estimated using Synthetic Aperture Radar (SAR) data from TerraSAR-X/TanDEM-X (TSX/TDX) and Sentinel-1A and -1B and optical imagery from Landsat 8 and 9.

## 1.1 Parameters

Velocity estimates, in meters per year, are provided as velocity magnitude ($v_v$), x and y component velocities ($v_x$, $v_y$), and x and y component velocity errors ($e_x$, $e_y$). In addition, to assess potential temporal skew in the velocity estimates, a temporal offset parameter (dT) is included that reports the number of days between the measurement date[1] and the midpoint date of the measurement period.

## 1.2 File Information

### 1.2.1 Format

Data are provided as cloud optimized GeoTIFFs (.tif) and shapefiles. TIFF and JPEG browse files are also available.

### 1.2.2 File Contents

Separate data files are available for each quarter (i.e., three month period). Quarters are defined as:

- 1 December – 28/29 February
- 1 March – 31 May
- 1 June – 31 August
- 1 September – 30 November

Each of the parameters listed above is provided as a separate, quarterly GeoTIFF file. Quarterly shapefiles are also available that indicate the source of the image pairs (i.e., SAR or Landsat) used to produce the mosaics.

[1]Because of the data aggregation process, the true date represented by the data may differ from the nominal midpoint date of the measurement period. See “2.3.3 | Temporal Offset Calculation” for details.

## 1.2.3 Naming Convention

### 1.2.3.1 GeoTIFF

**Naming Convention:**

[product name]_[start date]_[end date]_[parameter]_[version].[ext]

**Example:**

GL_vel_mosaic_Quarterly_01Dec14_28Feb15_vv_v05.0.tif
GL_vel_mosaic_Quarterly_01Dec14_28Feb15_vx_v05.0.tif
GL_vel_mosaic_Quarterly_01Dec14_28Feb15_vy_v05.0.tif
GL_vel_mosaic_Quarterly_01Dec14_28Feb15_ex_v05.0.tif
GL_vel_mosaic_Quarterly_01Dec14_28Feb15_ey_v05.0.tif
GL_vel_mosaic_Quarterly_01Dec14_28Feb15_dT_v05.0.tif

The following table describes the variables in the GeoTIFF file naming convention:

Table 1. GeoTIFF File Naming Convention

| Variable | Description |
|---|---|
| product name | GL_vel_mosaic_Quarterly (Greenland Quarterly Ice Sheet Velocity Mosaics) |
| start date | Start date of measurement period (DDMMMYY) |
| end date | End date of measurement period (DDMMMYY) |
| parameter | vv (velocity magnitude)<br>vx, vy (component velocity)<br>ex, ey (component velocity error)<br>dT (temporal offset) |
| version | Two digit version, plus release number (when applicable). E.g., V05.0 the initial release of Version 5. |
| ext | File extension (.tif) |

### 1.2.3.2 Shapefile

**Naming Convention:**

[product name]_[start date]_[end date]_[source]_[version].[ext]

**Example:**

GL_vel_mosaic_Quarterly_01Dec14_28Feb15_LS_v05.0.dbf
GL_vel_mosaic_Quarterly_01Dec14_28Feb15_LS_v05.0.prj
GL_vel_mosaic_Quarterly_01Dec14_28Feb15_LS_v05.0.shp
GL_vel_mosaic_Quarterly_01Dec14_28Feb15_LS_v05.0.shx

The following table describes the variables in the shapefile file naming convention:

Table 2. Shapefile File Naming Convention

| Variable Name | Description |
|---|---|
| product name | GL_vel_mosaic_Quarterly (Greenland Quarterly Ice Sheet Velocity Mosaics) |
| start date | Start date of measurement period (DDMMMYY) |
| end date | End date of measurement period (DDMMMYY) |
| source | SAR or LS (Landsat 8/9) |
| version | Two digit version, plus release number (when applicable). E.g., V05.0 = Version 5 (initial release). |
| ext | File extension. For this data set, a complete shapefile consists of four file types:<br>.dbf (dBASE table file)<br>.shp (main file)<br>.shx (index file)<br>.prj (projection definition file) |

#### 1.2.3.3 Browse Images

Browse images follow the same naming convention described above, but include the word “browse” in the file name and either the "tif” or “jpg” file extension. For example:

GL_vel_mosaic_Quarterly_01Dec14_28Feb15_browse_v05.0.jpg
GL_vel_mosaic_Quarterly_01Dec14_28Feb15_browse_v05.0.tif

## 1.3 Spatial Information

### 1.3.1 Coverage

Data span the Greenland Ice Sheet as follows:

Northernmost Latitude: 83° N
Southernmost Latitude: 58.5° N
Easternmost Longitude: 8.32° W
Westernmost Longitude: 90.9° W

### 1.3.2 Resolution

Data are posted at 200 m. JPEG browse files are 500 m resolution.

Note that this resolution does not reflect the true "on the ground" resolution. The velocities are derived from source data with spatially varying averages that range from a few hundred meters to 1.5 km, making it difficult to specify the resolution at any point.

For example, some estimates represent the average of 30 or more individual measurements. While this enhances the final resolution to some degree relative to the individual source products, the amount is not well quantified.

For work requiring finer resolution, users may prefer the individual TerraSAR-X (TSX)/TanDEM-X (TDX) and Landsat data where available (see MEaSUREs Greenland Ice Velocity: Selected Glacier Site Velocity Maps from InSAR and MEaSUREs Greenland Ice Velocity: Selected Glacier Site Velocity Maps from Optical Images).

### 1.3.3 Geolocation

The following tables provide information about geolocating this data set. Velocity-related GeoTIFFs are provided in the NSIDC Sea Ice Polar Stereographic North projection (see Table 3). Shapefiles are geolocated with WGS 84 latitudes and longitudes (see Table 4).

Table 3. NSIDC Sea Ice Polar Stereographic North (EPSG:3413)

| | |
|---|---|
| **Geographic Coordinate System** | WGS 84 |
| **Projected Coordinate System** | WGS 84 / NSIDC Sea Ice Polar Stereographic North |
| **Longitude of True Origin** | -45 |
| **Latitude of True Origin** | 70 |
| **Scale factor at longitude of true origin** | 1 |
| **Datum** | WGS 1984 |
| **Ellipsoid/spheroid** | WGS 84 |
| **Units** | meter |
| **False Easting** | 0 |
| **False Northing** | 0 |
| **EPSG Code** | 3413 |
| **PROJ4 String** | +proj=stere +lat_0=90 +lat_ts=70 +lon_0=-45 +k=1 +x_0=0 +y_0=0 +datum=WGS84 +units=m +no_defs |
| **Reference** | http://epsg.io/3413 |

Table 4. World Geodetic System 1984 (EPSG:4326)

| | |
|---|---|
| **Geographic Coordinate System** | WGS 84 |
| **Projected Coordinate System** | N/A |
| **Longitude of True Origin** | 0° |
| **Latitude of True Origin** | N/A |
| **Scale factor at longitude of true origin** | N/A |
| **Datum** | World Geodetic System 1984 |
| **Ellipsoid/spheroid** | WGS 84 |
| **Units** | degree |
| **False Easting** | N/A |
| **False Northing** | N/A |
| **EPSG Code** | 4326 |
| **PROJ4 String** | +proj=longlat +datum=WGS84 +no_defs |
| **Reference** | http://epsg.io/4326 |

## 1.4 Temporal Information

### 1.4.1 Coverage

1 December 2014 to 30 November 2024

### 1.4.2 Resolution

Quarterly, with quarters defined as follows:

- 1 December – 28/29 February
- 1 March – 31 May
- 1 June – 31 August
- 1 September – 30 November

# 2 DATA ACQUISITION AND PROCESSING

## 2.1 Acquisition

The velocity mosaics in this data set were produced from SAR data acquired by the European Space Agency (ESA) Sentinel-1A and Sentinel-1B satellites, supplemented with TSX/TDX data for coastal outlets. The data were acquired in either 12-day (through Sept 2016) or 6-day repeat cycles (October 2016 forward). In cases of missing acquisitions, the repeat periods may be longer (integer multiples of 6 or 12 days) for some of the image pairs.

In addition, during periods with sufficient daylight, velocities derived from optical imagery acquired by Landsat 8 and Landsat 9 were used to supplement the SAR data.

### 2.1.1 Annual Variation in Data Acquisition

**2015 (Dec 1, 2014 – Nov 30, 2015)**
Sentinel-1A data acquisitions began in 2015, but the acquisition rates were not as regular as in later years. As a result, these data tend to be somewhat noisier than the 2016 data, particularly in the middle of the ice sheet. In addition, the sampling of coastal regions is more irregular (there are gaps in the temporal coverage where TSX/TDX data were not acquired by the satellite for a month or more), which reduces the averaging of seasonal variation.

**2016 (Dec 1, 2015 – Nov 30, 2016)**
For this year, the six Sentinel-1A tracks that image the majority of the Greenland coast were collected for almost every 12-day satellite repeat cycle. Beginning in October 2016, Sentinel-1B started acquiring data over Greenland in an orbit that lags Sentinel-1A by six days, providing better coverage and thus more correlations in the data. As a result, accuracy for these mosaics is considerably better than the mosaics for 2015 for most regions.

**2017 (Dec 1, 2016 – Nov 30, 2017)**
These products are similar to the earlier 2015 and 2016 products. The major difference is that this is the first year that regular 6-day coverage occurred throughout the year, which should improve

performance on fast moving glaciers. In addition, the Copernicus Sentinel mission improved coverage for the southern part of Greenland in mid-2017, so the results should be improved for areas south of 67.5 degrees.

**2018 (Dec 1, 2017 – Nov 30, 2018)**
These products follow the same specifications as the previous year's release, with the following minor differences: some data using a few scenes from the COnstellation of small Satellites for the Mediterranean basin Observation (COSMO-SkyMed) were included; some of the glaciers which were monitored by TSX in past years are covered by other instruments during this year.

**2019 (Dec 1, 2018 – Dec 31, 2022)**
No changes. See specifications for previous releases.

**2023 (Jan 1, 2022 – present)**
From 2022 onward, these products utilize Landsat 9 observations, when available.

## 2.2 Processing

These mosaics were computed as averages of all available data at each point, weighted by their respective errors, following Joughin, 2002. In addition to speckle/feature tracking, interferometric phase data are utilized when possible to improve accuracy (Joughin et al., 2017).

With Sentinel-1 TOPS mode, azimuth motion introduces phase discontinuities at burst boundaries (roughly every 20 km) because the radar squint angles differ at the fore and aft edges of each burst. These errors were corrected by using an existing velocity map[2] to model and remove burst discontinuities similar to the procedure described by Andersen et al. (2020). Phase discontinuities introduced by the ionosphere were reduced by processing the interferograms using the InSAR Computing Environment (ISCE) with the ionospheric correction enabled (Fattahi et al., 2017).

ⓘ For non-winter quarters, little if any phase data is included in the solution because most phase data are concentrated during December to February. While the inclusion of phase data in certain areas during these quarters does reduce errors substantially relative to earlier versions, the overall impact to the quarterly data product is sporadic.

### 2.2.1 Baseline Fits

Each azimuth and range offset swath product used to produce the mosaics must be calibrated, to determine parameters related to the relative positions of the satellites when the images in a pair

[2] MEaSUREs Multi-year Greenland Ice Sheet Velocity Mosaic, Version 1 (NSIDC-0670)

were collected. As such, regressions are used to construct baseline fits to sets of control points with known velocity and elevation, thus capturing the along-track variation in the parameters.

Along the slow-moving ice divides, where speeds are < 5 m/y, the data are calibrated using balance velocities[3] (Bamber et al., 2000), estimated by computing surface mass balance (SMB) as the average of two models—the Regional Atmospheric Climate Model, Version 2.3 (RACMO2.3) and the Modèle Atmosphérique Régionale, Version 3.12 (MAR3.12)—both averaged over the period from 1958 to 2021.

With Sentinel-1, greater reliance can be placed on the knowledge of the parameters derived from the orbital state vectors. As a result, these data are calibrated by using the fitting process to determine a constant for each parameter, rather than a quadratic function, allowing the along-track dependence to be determined directly from the state vectors.

For periods where data are not well controlled (sparse ground control points), control points from other periods with adequate controls are used. This greatly improves consistency of the data from quarter to quarter. While this could mask some true change, the errors without this procedure are far larger than any change likely to occur.

### 2.2.2 Aggregation and Weighting

For each quarter, all available data are aggregated and combined in an error-weighted method to achieve an optimal estimate with respect to error reduction. However, due to limited coverage or lack of unsuccessful matches, there are data gaps such that the full three month period may not be sampled uniformly.

In order to maximize coverage, data were included where the sampling interval of the input data did not fully lie within the output interval. In these cases, the data are weighted by the amount they overlap the output interval (e.g., if the first 6 days of a 12-day image pair lie within the output interval, a weight of 0.5 would be applied). If uniformly sampled data, e.g., every 12 days, and uniformly weighted data were combined, this procedure would be equivalent to a linear interpolation of the time series.

Finally, to reduce error and improve coverage, data were also included where the input estimate spanned an interval longer than the output interval (e.g., up to a five month pair for the three month output). This inclusion slightly degrades the temporal resolution, but improves coverage and helps reduce errors. Weights are applied to data spanning more than three months to deemphasize their

[3]Balance velocities represent depth-averaged speeds in the downslope direction that would result if the amount of snow added annually to a volume of the ice sheet equaled the amount of mass lost from that volume via advection or melting.

contribution, such that they only factor into estimates where coverage from other data is poor. As such, while the nominal, three month resolution is valid for most of the data set, the actual resolution can be lower in some regions.

### 2.2.3 Submergence/Emergence Velocity

The submergence/emergence velocity (i.e., the vertical motion of the ice surface) is removed using an average of RACMO2.3 and MAR3.12 SMB for the period 1958 to 2021.

### 2.2.4 Temporal Offset Calculation

As a measure of temporal skew, a mean temporal offset (dT) is provided which reports the number of days between the measurement date—the dates of the image pairs, adjusted by any weighting applied when computing the component velocities—and the midpoint date of the measurement period.

In detail, dT is computed as follows:

1. Using a Day of the Year (DOY) calendar, determine the midpoint for the measurement period i.e., quarterly, monthly or annual.
2. For each pixel, identify the image pairs used as input for velocity and calculate the central DOY date.
3. Calculate a weighted average central date for that pixel by using an intermediate weight, based on the weights used to compute the $v_x$ and $v_y$ components.
4. dT = weighted average central date – midpoint.

Although the averaged dT value provides some idea of the deviation from nominal date, users should be cautious when using dT to correct dates.

For example, for a quarterly mosaic that covers the period 1 March – 31 May, the nominal center date is 15 April. If dT = 10, then 25 April would better represent the midpoint date for the parameters in this interval.

However, there are convoluted cases that could also result in dT = 10. For example, say the mosaic was produced using images collected from 13–24 March and 5–18 May. In this case, dT would equal 10 with no measurement from April 25. Alternatively, a mosaic produced using a single pair from 20–30 April would also have dT = 10, but with a sample from April 25.

The data providers recommend using dT to flag potential time skew issues, rather than for date correction. In cases where a large temporal skew exists, other GrIMP products with finer temporal sampling are likely better suited for analyzing temporally varying behavior.

### 2.2.5 Interpolated Points

Small gaps in the final maps have been filled via interpolation. These points can be identified as those that have valid velocity data but no corresponding error estimate. See Joughin et al. (2002) for more detail on errors and how they were computed.

### 2.2.6 Areas with No Data

Areas with no data correspond either to regions where no data were acquired or where the interferometric or optical correlation was insufficient to produce an estimate. This occurs most often in areas with high snow accumulation. The no data value for vv, ex, and ey files is -1. The no data value for vx, vy, and dT is -2e9.

### 2.2.7 GDAL-Generated Cloud Optimized GeoTIFFs

The GeoTIFFs were generated using Geospatial Data Abstraction Library (GDAL), to make them compatible with the latest cloud optimized GeoTIFF format. GDAL generates previews for Cloud Optimized GeoTIFFs; however, the software uses cubic interpolation that results in minor artifacts around the lower resolution previews. Averaging is used to avoid this issue.

ⓘ When GDAL creates cloud optimized GeoTIFFs, it writes image statistics directly to the file header.

## 2.3 Quality, Errors, and Limitations

These data do not represent true quarterly averages due to the weighting schemes. For example, in some places mid-summer may be weighted more heavily than mid-winter due to the seasonal availability of Landsat 8 and 9 data. Similarly, clouds or large snow accumulation events may affect the seasonal distribution of the data.

As a result, these data should not be used to determine inter-annual change for interior regions of the ice sheet (roughly defined as areas above 2,000 m). In outlet glaciers close to the coast where the baselines are well constrained by bedrock, the velocity mosaics are better suited to this task. However, care should be exercised in interpreting any change observed in intermediate regions (roughly 1000 m to 2000 m), i.e., avoid areas where the observed changes seem to follow a satellite swath boundary (Refer to Figure 5 in Phillips et al., 2013, for an example.).

In general, the error estimates represent the average behavior of the data. This means that errors may be much lower than reported in some areas and much greater in others; care should be taken when assigning statistical significance based on the errors, especially given that the errors can be correlated over large areas. For example, even if the errors are correct in a global sense, one might

compare two mosaics and find a large difference over 5% of the ice sheet. However, because errors can be spatially correlated over broad areas, one should not assume significance at the 95% confidence level; this might be precisely the 5% that statistically should exceed the errors because the errors are not uniformly distributed. By contrast, if the errors were completely uncorrelated one could average over neighborhoods to reduce the error.

While the data are posted at 200 m, the true resolution varies between a few hundred meters to 1.5 km, depending on the resolution at which the data were collected. Many small glaciers are resolved outside the main ice sheet, but for narrow (<1 km) glaciers, the velocity represents an average of both moving ice and stationary rock. As a result, while the glacier may be visible in the map, the actual speed may be underestimated. For smaller glaciers, interpolation produces artifacts where the interpolated value is derived from nearby rock, causing apparent stationary regions in the middle of otherwise active flow. The data have been screened to remove most of these artifacts, but should be used with caution.

In areas where Sentinel-1A and -1B ascending and descending crossing orbit data were available, an error-weighted range-offset-only solution was included in the velocity algorithm. Where these data are included, the errors are generally substantially lower than solutions with azimuth offsets, which can be subject to large errors due to ionospheric streaking. However, by virtue of the error weighting, the range-offset-only solutions tend to dominate the aggregate output and yield more accurate results.

Regarding the use of balance velocities, although they may have large errors in a relative sense, by limiting their use to slow-moving regions, any errors should be small in an absolute sense.

User should also note that the correction for ice-equivalent submergence/emergence velocity may be impacted by recent increases in melt. However, this parameter should evolve over decadal or greater timescales for much of the ice sheet.

In addition, this correction does not account for firn compaction due to the large uncertainties in penetration depth and compaction rates. For the bare-ice zone, where the correction tends to be the largest, this omission should have no effect. For firn covered areas, the correction may underestimate the true submergence/emergence velocity by up to a few tens of centimeters per year. However, the results still represent an overall improvement in accuracy.

Finally, this product uses a variation of the GrIMP DEM (see NSIDC-0715) which has a lower resolution of 270 m and utilizes geoidal heights for the ocean. The DEM also contains a correction to a 15m horizontal shift that was identified previously.

# 3 INSTRUMENTATION

- European Space Agency (ESA)
  - Sentinel-1
- Deutsches Zentrum für Luft- und Raumfahrt (DLR)
  - TerraSAR-X (TSX)
  - TanDEM-X (TDX)
- U.S. Geological Survey (USGS)
  - Landsat 8
  - Landsat 9

# 4 SOFTWARE AND TOOLS

GeoTIFF files and shapefiles can be viewed with a variety of Geographical Information System (GIS) software packages including QGIS and ArcGIS.

# 5 VERSION HISTORY

Table 5. Version History Summary

| Version | Release Date | Description of Changes |
|---|---|---|
| 5.0 | Mar 2025 | • Temporal coverage extended through 30 Nov 2024 |
| 5.0 | Sep 2024 | • Added coverage from 1 Sep 2023 through 31 May 2024.<br>• An update to the Python library used to generate this data set's ShapeFiles has resulted in field names being truncated to 10 characters instead of 11. As such, the "PercentGood" field name appears as "PercentGoo" in all ShapeFiles added after Mar 2023. |
| 5.0 | Mar 2023 | • Improved correction for submergence/emergence velocity using an average of RACMO2.3 and MAR3.12 SMB for the period from 1958 to 2021<br>• Calibration improved by using an improved balance velocity estimate, computed as the average of RACMO2.3 and MAR3.12, and by excluding GPS points >2000 m from the 1990s.<br>• Solid Earth tides corrected using PySolid (https://github.com/insarlab/PySolid)<br>• Includes Landsat 9 data from 2022 onward<br>• Landsat-specific data files now designated by "LS" in the file name (instead of "LS8" as in previous versions). |
| 4.0 | Aug 2022 | • Temporal coverage extended<br>• Data recalibrated relative to previous versions to reduces biases imposed by quadratic fits to control points<br>• Correction added for the submergence/emergence velocity<br>• Addition of interferometric phase data where available. |

| Version | Release Date | Description of Changes |
|---|---|---|
| 3.0 | Jun 2021 | • Use of GDAL 3.2.1 to create cloud optimized GeoTIFFs<br>• Update of temporal coverage<br>• Data reprocessed utilizing a corrected DEM. See user note in section 2.2 |
| 2.0 | Dec 2020 | • New file naming convention<br>• Data set temporal range increased by one year from: 01 December 2014 to 30 November 2019.<br>• Application of a new DEM, NSIDC-0715; prior versions relied on NSIDC-0646<br>• All files have a 200 m resolution with the exception of the browse.jpg which is at 500 m; 500 m resolution velocity files no longer available<br>• A more rigorous culling of the data removed bad data and added previously overlooked data. As a result, mosaics show more areas with no data, the min/max ex and ey values are lower, and SAR/LS8 feature counts differ from Version 1.<br>• The no data value for vv changed from -0.1 to -1; the no data value for ex and ey changed from -2e9 to -1.<br>• Newly available are cloud optimized GeoTIFFs along with tif.aux.xml, and jpg.aux.xml files. |
| 1.1 | Oct 2019 | Updated .tif file names within .vrt files to match the actual .tif file names |
| 1.0 | Feb 2018 | Initial release |

# 6 RELATED DATA SETS

- MEaSUREs Greenland Annual Ice Sheet Velocity Mosaics from SAR and Landsat
- MEaSUREs Greenland Monthly Ice Sheet Velocity Mosaics from SAR and Landsat
- MEaSUREs Greenland Ice Velocity: Selected Glacier Site Velocity Maps from InSAR
- MEaSUREs Greenland Ice Sheet Velocity Map from InSAR Data

# 7 RELATED WEBSITES

- MEaSUREs Data | Overview
- Alaska Satellite Facility
- Greenland Ice sheet Mapping Project (GrIMP)

# 8 CONTACTS AND ACKNOWLEDGMENTS

## 8.1 Contacts

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## 8.2 Acknowledgments

This project was supported by a grant from the NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) Program.

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# 10 DOCUMENT INFORMATION

## 10.1 Publication Date

March 2023

## 10.2 Date Last Updated

April 2025